

The NHMFL/NSCL Sweeper Magnet

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Florida State University (FSU) and Michigan State University (MSU) are engaged in a collaboration to build a sweeper magnet for radioactive beam experiments. The magnet is being built at the NHMFL at FSU and will be operated at MSU's National Superconducting Cyclotron Laboratory (NSCL). The NSF is the primary funding source for both laboratories, as well as this project.

Nuclear Physics Opportunities

The NSCL has recently coupled their two cyclotrons such that the older K500 supplies beam to the newer K1200. This new, coupled configuration offers a unique opportunity to create nuclei along the neutron dripline up to the Sulfur isotopes, a capability presently not available elsewhere in the world. Neutron coincidence experiments will be a major part of the future experimental program at the NSCL and a large gap deflection magnet is necessary to sweep away the beam and the charged fragments from the neutrons.

The NSCL has an S800 mass spectrograph, which is a unique device for charged particle detection. The sweeper magnet will add the capability to perform neutron coincidence experiments. The combination of the sweeper magnet with the S800 will allow simultaneous high resolution momentum distribution measurements of the fragments and neutrons in the decay of halo nuclei and full kinematic reconstruction of neutron unbound states (excited states of nuclei close to the driplines and ground states of nuclei beyond the driplines). In both types of experiments, the magnet sweeps the beam away from zero degrees where the neutrons will be detected with the neutron walls. At the same time, the charged fragments are deflected by the sweeper magnet into the S800 (located at 40°).

The magnet will also play an important role in decay studies along the proton dripline. The study of proton decay of ground and excited states along the proton

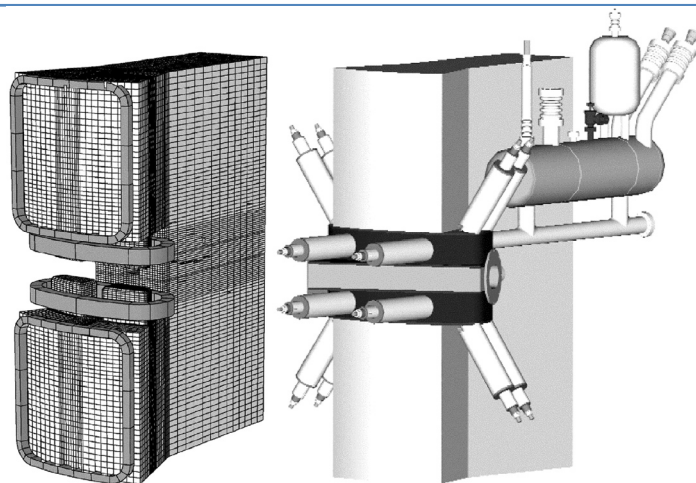


Figure 1. Electromagnetic model of the sweeper magnet (left) with design model (right).

dripline similar to the neutron decay experiments will be possible with its use as will the search for di-proton emitters. For very low decay energy, both the fragments and the proton(s) are emitted near zero degrees in the laboratory rest frame. Thus, a bending magnet is necessary to separate the fragments from the protons before they are detected and identified. Again, the S800 is the ideal detector for the heavy fragment, whereas a high resolution $\Delta E/E$ detector array can be used with the sweeper magnet for proton detection.

In order to use the most rigid beams from the coupled cyclotron facility a focal plane detector similar to the S800 is being built and the sweeper magnet will be used in a “stand alone” mode. The magnet will then be set up in the new N4 vault, which is being extended as part of the coupled cyclotron upgrade. The resulting longer flight path will increase the energy resolution of the neutron walls for the neutron coincidence experiments. Coupled with a quadrupole magnet, the sweeper magnet will also be used as a broad range spectrometer that will allow the gamma rays of higher-lying intermediate energy Coulomb inelastic excitations to be distinguished from the gamma rays produced from excited single nucleon transfer products for masses up to $A = 50$.

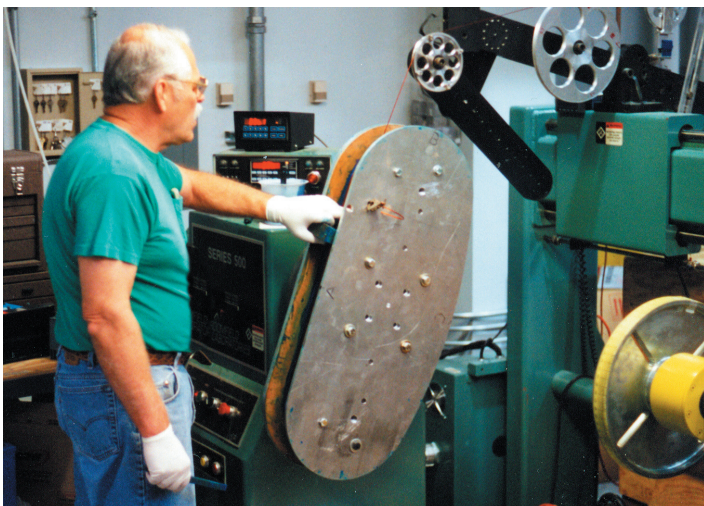


Figure 2. Winding of superconducting coil for sweeper magnet at the NHMFL.

Magnet Design

Electromagnetically, the sweeper magnet consists of two “D” shaped NbTi superconducting coils, a twenty ton “C” shaped iron yoke, and two square resistive trim coils as shown in Fig. 1.

From an assembly perspective, the magnet consists of five major sub-assemblies: the magnet cryostat, the satellite cryostat, the resistive coils, the magnet iron, and the power supplies as shown in Fig. 1. The magnet cryostat, in turn, consists of the two NbTi coils (Fig. 2); a stainless steel bobbin (Fig. 3) that serves as the main structural support and as the helium vessel; structural links from 300 K to 4 K; a nitrogen shield; and a vacuum vessel. The satellite cryostat consists of the helium reservoir, the nitrogen reservoir, nitrogen shields, warm-to-cold links, vapor-cooled leads, bus work and a joint, and a vacuum vessel.

While the magnet provides only modest field (4.0 T on the beam-line and 6.3 T on the conductor) it remains a substantial challenge due primarily to the large gap, non-circular coils, and space constraints. For example, the forces separating the legs of the coils are about 145 metric tons. Such forces require substantial structural support be provided by the bobbin. Not only does the bobbin have to be strong enough to withstand the forces, but it must also be sufficiently stiff to limit coil strain to an acceptable limit.

In addition, the interface between the coil and the bobbin is a very critical design feature. The strain

energy density of the magnet is as high as $39 \mu\text{J}/\text{mm}^3$. The energy margin of the coils is about $7 \mu\text{J}/\text{mm}^3$. If we divide the total electromagnetic stored energy of the coils by their volume, we get $13,240 \mu\text{J}/\text{mm}^3$. Sliding or cracking at the coil/bobbin interface can easily convert sufficient stored energy into heat raising the coil above its current sharing temperature and initiating a quench. Indeed, the smaller “Superbend” magnets that were recently built for the Advanced Light Source at Lawrence Berkeley National Laboratory have similar shape and operate at similar field and current density, and they suffered from numerous training quenches.¹

To fully understand the electromagnetic and structural issues associated with the coil/bobbin interface, several man-months of effort were spent performing detailed three-dimensional finite element calculations of field, body force, and stress distribution with various assumed values of the coefficient of friction. Numerous iterations of coil and bobbin shape were performed to reduce peak stresses and to increase serviceability of the magnet.

Another feature of the design of this coil/bobbin system is the fact that the bobbin has to be welded shut around the coil. The bobbin is made of a stainless steel plate 1/2” to 3/4” thick. Due to the large electromagnetic forces on the coils, the bobbin experiences high stresses, particularly in the weld areas. Nearly full-penetration, crack-free welds are required with very low delta ferrite content to provide sufficient strength, stiffness, and fracture toughness at liquid helium temperatures. In addition, one must avoid overheating the coil during the welding process. Extensive practice welding was performed using various cooling methods to minimize coil heating. The finished practice welds were then tested at low temperature to measure strength, toughness, and ferrite content prior to final selection of welding materials, processes, and operators.

The final coil/bobbin interface system includes a slip surface between the coil and bobbin, an insulating layer between the coil and the slip surface, a helium ventilation scheme, a stiff and strong support, and a low-cost construction, all within a 5 mm space outside the coil.

Finally, the coils and bobbin have to be kept at 4.5 K. While reaching this temperature is typically not a major challenge, in this case the space constraints

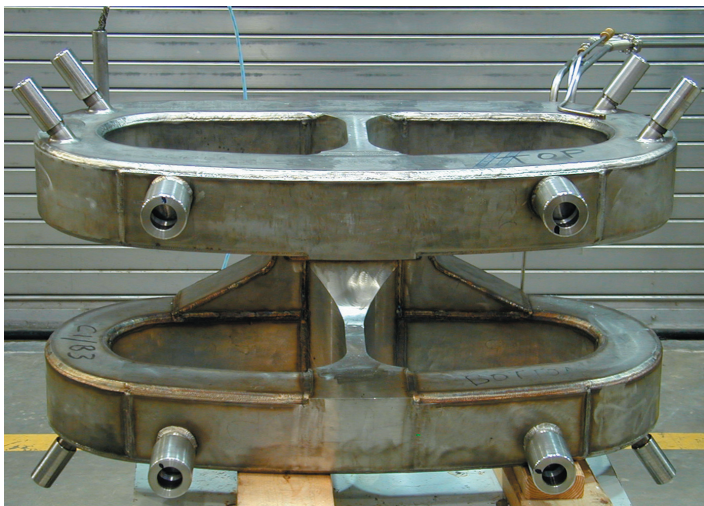


Figure 3. The stainless steel bobbin serves as a helium vessel and the main structural element.

require very small clearance between the 4.5 K bobbin, the 77 K nitrogen shield, and the 300 K vacuum jacket. Over much of the cryostat volume, the space between 4.5 K and 300 K is only 25 mm. The need to combine this tight clearance with a complicated shape lead us to develop a novel laminated nitrogen shield design that provides excellent cooling in very tight spaces. Even with this innovation, however, the cryostat remains a serious challenge.

The wire and coil parameters for the superconducting coils are presented in Table 1. The coils are designed to operate at fairly high overall current density and high stress. The fraction of critical current was intentionally kept low to provide a substantial energy margin to reduce the probability of quenching as well as to facilitate meaningful bucket testing of the coils. The wire is 1 mm x 2 mm with a copper to superconductor ratio of 1.8:1. It is wet wound with stycast and interlayer glass cloth. Stycast was chosen for winding as its thermal contraction on being cooled to helium temperatures is very similar to that of the steel bobbin. Using a dry-wind and impregnation scheme would result in gaps opening during cool-down that may contribute to training and/or degradation.

Three coils were wound between December 2001 and February 2002. Roll bending and welding of the three half-bobbins started in October 2001.

Fabrication Status

The coils were welded into their half-bobbins and tested to high current, field, and strain. The first was

MAGNETIC PARAMETERS AND WIRE SPECIFICATIONS

Peak field on conductor (T)	6.27
Max. field on beam-line (T)	3.96
Coil pack average current density (A/mm ²)	143
Current (A)	365
I/lc	0.28
Stored energy (kJ)	930
Heat load (l/hr of helium)	<10
Turns/layer	46
# of layers	56
Critical current @ 5.27 T (A)	1312
Bare wire height (mm)	1.9
Bare wire width (mm)	0.9
Insulation material	FORMVAR
Insulation thickness (mm)	0.05
Cu:SC ratio	1.8:1
Corner radius (mm)	0.3
Filament size (mm)	46
Twist pitch (mm)	32
RRR	64

completed in May, the second in July, and the third in August of this year (Fig. 4). The test data indicate some variation between the three-coil/bobbin assemblies and the two best (numbers 1 and 3) have been chosen for installation in the final user magnet. The test data suggest that the final user magnet should reach design current with minimal training. The two half-bobbins have been welded together to form the final full bobbin. A joint has been made between the two coils, the lead supports have been installed, and the joint box has been welded shut and leak checked (Fig. 3). As of this writing (late November), construction of the nitrogen shield is underway, to include leak checking.

Then the vacuum jacket will be welded together around the shield, also requiring leak checking. That will complete the assembly of the magnet cryostat.

Satellite cryostat fabrication will follow a similar pattern to that of the magnet cryostat: helium circuit, nitrogen circuit, vacuum jacket, each with an extensive leak check procedure.

Once the magnet and satellite cryostats are complete, they will be brought together and a joint in the



Figure 4. A coil /bobbin assembly is installed in a dewar at the NHMFL for high field testing.

superconducting circuit will be made inside the “services duct” that connects them. The services duct will be closed; again; helium, nitrogen and vacuum, each with extensive leak testing.

When the services duct has been closed, the complete cryostat will be installed in the 20 tons of iron presently located in resistive magnet cell 2, connected to a power supply, energized, and the field will be measured. Once testing is complete, the magnet can be disassembled into pieces less than 2.5 tons and shipped to the NSCL where it will be re-assembled, re-tested, and combined with the beamline, neutron detectors, mass spectrometers, etc., to perform novel nuclear physics experiments as described above.

Acknowledgments

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		Vaughn Williams	
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¹ C.E. Taylor, *et al.*, *IEEE Trans. on Appl. Supercond.*, **9**, 2, 479-482. (1999).

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